

Contents lists available at [ScienceDirect](http://ScienceDirect)

## Physics Letters B

[www.elsevier.com/locate/physletb](http://www.elsevier.com/locate/physletb)Constraining new physics in  $B^0 \rightarrow \pi^+\pi^-$  with reparametrization invariance and QCD factorization

Patricia Ball, Aoife Bharucha\*

IPPP, Department of Physics, University of Durham, Durham DH1 3LE, UK

## ARTICLE INFO

## Article history:

Received 14 July 2009

Received in revised form 28 September 2009

Accepted 7 October 2009

Available online 9 October 2009

Editor: G.F. Giudice

## PACS:

13.25.Hw

11.30.Er

12.15.Hh

12.60.-i

## Keywords:

B-Physics

CP violation

Beyond Standard Model

## ABSTRACT

Usually,  $B^0 \rightarrow \pi^+\pi^-$  decays are expressed in terms of weak amplitudes explicitly dependent on the CKM weak phase  $\alpha$  or  $\gamma$ . In this Letter, we show that the weak amplitudes can be rewritten such that a manifest dependence on  $\beta$  emerges instead. Based on this, we constrain new-physics contributions to the CP-violating phase  $\phi_d$  in  $B^0$ – $\bar{B}^0$  mixing. Further, we apply reparametrization invariance and use QCD factorization predictions to investigate the bounds on an additional new-physics amplitude in  $B^0 \rightarrow \pi^+\pi^-$ .

© 2009 Elsevier B.V. Open access under [CC BY license](http://creativecommons.org/licenses/by/3.0/).

One of the greatest successes of the  $B$  factories BaBar and Belle is the precise determination of the CP-violating phase  $\phi_d$  in  $B$  mixing [1]. In the Standard Model (SM), and using the Wolfenstein parametrization of the CKM matrix,  $\phi_d$  is related to  $\beta$ , one of the angles of the unitarity triangle, as  $\phi_d = 2\beta$ . As  $B$  mixing is a loop process, the experimentally determined angle  $\phi_d$  might in fact not equal  $2\beta$ , but be polluted by the effects of new-physics (NP) particles propagating in loops, thereby contributing an additional CP violating phase, see for instance Ref. [2]. It is therefore of considerable interest to study any methods by which one can constrain an additional NP contribution to  $\phi_d$ . In this Letter we shall show that the process  $B^0 \rightarrow \pi^+\pi^-$  can be used to this effect.

The set of neutral and charged  $B \rightarrow \pi\pi$  decays has been extensively studied as a means of determining the angle  $\alpha$  (or  $\gamma$ ) of the unitarity triangle. The lack of a theoretically clean calculation of the strong amplitudes and phases involved can be overcome by exploiting isospin symmetry, see Ref. [3], commonly referred to as the Gronau–London method. It involves relating the various

experimental observables (branching ratios and CP asymmetries) in  $B \rightarrow \pi\pi$  to extract both the hadronic amplitudes determining these decays and the weak phase  $\alpha$ . As an alternative to isospin, and in order to avoid  $B^0 \rightarrow \pi^0\pi^0$  decays, the use of U-spin has been explored in Refs. [4] to extract  $\gamma$  from  $B^0 \rightarrow \pi^+\pi^-$  and the U-spin related decay  $B_s \rightarrow K^+K^-$ . In a conceptionally different approach the relevant strong amplitudes are calculated (as opposed to extracted from experiment), using QCD factorization (QCDF) [5–8] or effective field theory methods (SCET) [9]. The advantage here is that less experimental input is needed, the disadvantage that the calculation is performed in a limit of QCD where the  $b$  quark is assumed to be very heavy. In any case, all these analyses put the emphasis on constraining the angles  $\gamma$  or  $\alpha$ .

In this Letter, we show that it is possible to express the decay amplitude in terms of  $\phi_d$  and  $\beta$ , without any explicit reference to the angles  $\alpha$  or  $\gamma$ . In the SM, the resulting expression allows the extraction of the relevant hadronic parameters from  $B^0 \rightarrow \pi^+\pi^-$  data alone, which can be compared to the theoretical calculation in QCDF. Beyond the SM, we study the possible presence of NP in this decay, which might contribute through  $B^0$ – $\bar{B}^0$  mixing via a NP contribution to  $\phi_d$  or through an additional NP amplitude.

We begin with a reminder of the parametrization used to extract  $\gamma$ . The amplitude for  $\bar{B}^0 \rightarrow \pi^+\pi^-$  is given in the form:

\* Corresponding author.

E-mail addresses: [Patricia.Ball@durham.ac.uk](mailto:Patricia.Ball@durham.ac.uk) (P. Ball), [a.k.m.bharucha@durham.ac.uk](mailto:a.k.m.bharucha@durham.ac.uk) (A. Bharucha).

**Table 1**

CKM parameters used in this Letter.

Parameter	Value	Source
$\lambda$	$0.2257^{+0.0009}_{-0.0010}$	PDG [10]
$ V_{cb} $	$(41.2 \pm 1.1) \times 10^{-3}$	PDG [10]
$ V_{ub} $	$(3.93 \pm 0.36) \times 10^{-3}$	PDG [10]
$\beta_{b \rightarrow ccs}$	$(21.1 \pm 0.9)^\circ$	HFAG [1]
$\beta_{\text{tree}}$	$(23.9 \pm 3.3)^\circ$	this Letter, Eq. (16)
$\gamma$	$(77^{+30}_{-32})^\circ$	PDG [10]
$R_b$	$0.412 \pm 0.039$	this Letter, Eq. (6)
$ V_{td} / V_{ts} $	$0.214 \pm 0.005$	[11]
$R_t$	$0.928 \pm 0.024$	this Letter, Eq. (10)

$$\mathcal{A}(\bar{B}^0 \rightarrow \pi^+ \pi^-) = \lambda_c A_c + \lambda_u A_u, \quad (1)$$

where  $\lambda_q = V_{qd}^* V_{qb}$ , and  $A_c, A_u$  are strong amplitudes.  $A_u$  is dominated by tree diagrams, whereas the only contributions to  $A_c$  are from penguin diagrams. The corresponding time-dependent CP asymmetry is given by:

$$A_{\pm}(t) = \frac{\Gamma(B^0(t) \rightarrow \pi^+ \pi^-) - \Gamma(\bar{B}^0(t) \rightarrow \pi^+ \pi^-)}{\Gamma(B^0(t) \rightarrow \pi^+ \pi^-) + \Gamma(\bar{B}^0(t) \rightarrow \pi^+ \pi^-)} = C_{\pm} \cos(\Delta m t) - S_{\pm} \sin(\Delta m t). \quad (2)$$

The experimental observables  $C_{\pm}$  and  $S_{\pm}$  can be expressed in terms of  $\lambda_{\pm}$ :

$$S_{\pm} = \frac{2 \text{Im}(\lambda_{\pm})}{1 + |\lambda_{\pm}|^2}, \quad C_{\pm} = \frac{1 - |\lambda_{\pm}|^2}{1 + |\lambda_{\pm}|^2}, \quad (3)$$

where  $\lambda_{\pm}$  is given by

$$\lambda_{\pm} = e^{-i\phi_d} \frac{\mathcal{A}(\bar{B}^0 \rightarrow \pi^+ \pi^-)}{\mathcal{A}(B^0 \rightarrow \pi^+ \pi^-)}. \quad (4)$$

Parametrizing the amplitudes as in Eq. (1), we have

$$\lambda_{\pm} = e^{-i\phi_d} \frac{e^{-i\gamma} - r e^{i\delta}}{e^{i\gamma} - r e^{i\delta}} \quad (5)$$

with  $r e^{i\delta} = A_c/(A_u R_b)$ ,  $\gamma = \arg(-\lambda_c/\lambda_u)$  and

$$R_b = \left| \frac{\lambda_u}{\lambda_c} \right| = \frac{1 - \lambda^2/2}{\lambda} \frac{|V_{ub}|}{|V_{cb}|}. \quad (6)$$

Numerical values for these and other CKM-related quantities are collected in Table 1. The observables  $S_{\pm}$  and  $C_{\pm}$  are given by

$$S_{\pm} = -\frac{\sin(\phi_d + 2\gamma) - 2r \sin(\phi_d + \gamma) \cos \delta + r^2 \sin \phi_d}{1 - 2r \cos \gamma \cos \delta + r^2}, \quad (7)$$

$$C_{\pm} = -\frac{2r \sin \gamma \sin \delta}{1 - 2r \cos \gamma \cos \delta + r^2}. \quad (8)$$

In the absence of penguin contributions,  $r = 0$  and the determination of  $\phi_d + 2\gamma$  would be completely analogous to that of  $\phi_d$  from  $B^0 \rightarrow J/\psi K_S$ . Realistically,  $r$  is expected to be a small, but non-zero number, which makes the extraction of  $\gamma$  more challenging.

We now show how a different parametrization of the decay amplitude (1) replaces the explicit dependence of  $\lambda_{\pm}$  on  $\gamma$  by one on  $\beta$ . Using  $\beta = \arg(-\lambda_t/\lambda_c)$ , one can trade the dependence on  $\gamma$  for one on  $\beta$  by exploiting the unitarity of the CKM matrix and exchanging  $\lambda_u$  for  $-\lambda_c - \lambda_t$ :

$$\mathcal{A}(\bar{B}^0 \rightarrow \pi^+ \pi^-) = \lambda_c B_c + \lambda_t B_t = \lambda_c (B_c - R_t e^{i\beta} B_t), \quad (9)$$

where  $B_c = A_c - A_u$ ,  $B_t = -A_u$  and

$$R_t = \left| \frac{\lambda_t}{\lambda_c} \right| = \frac{1}{\lambda} \frac{|V_{td}|}{|V_{ts}|} \left\{ 1 - \frac{1}{2} (1 - 2R_b \cos \gamma) \lambda^2 + O(\lambda^4) \right\}. \quad (10)$$

**Table 2**Experimental results for  $S_{\pm}$ ,  $C_{\pm}$  from BaBar and Belle and the HFAG average.

Experiment	$S_{\pm}$	$C_{\pm}$
BaBar [14]	$-0.68 \pm 0.10 \pm 0.03$	$-0.25 \pm 0.08 \pm 0.02$
Belle [15]	$-0.61 \pm 0.10 \pm 0.04$	$-0.55 \pm 0.08 \pm 0.05$
HFAG [1]	$-0.65 \pm 0.07$	$-0.38 \pm 0.06$

Note that  $B_c$  and  $B_t$  are both dominated by tree-level decays as they both contain  $A_u$ .

With this parametrization of the decay amplitude,  $\lambda_{\pm}$  becomes

$$\lambda_{\pm} = e^{-i\phi_d} \left( \frac{1 - R_t R_{tc} e^{i\beta}}{1 - R_t R_{tc} e^{-i\beta}} \right) \quad (11)$$

$$= e^{-i\phi_d} \left( \frac{1 - d e^{i\theta_d} e^{i\beta}}{1 - d e^{i\theta_d} e^{-i\beta}} \right), \quad (12)$$

where  $R_{tc} = B_t/B_c$  and  $d = |R_t R_{tc}|$ ,  $\theta_d = \arg(R_t R_{tc})$ . Note that unlike  $r$ ,  $d$  is not suppressed, but expected to be of order 1 (as  $R_t$  is also close to 1). The CP-violating observables in (3) now read

$$S_{\pm} = \frac{d^2 \sin(2\beta - \phi_d) + 2d \cos \theta_d \sin(\phi_d - \beta) - \sin(\phi_d)}{d^2 - 2d \cos \beta \cos \theta_d + 1}, \quad (13)$$

$$C_{\pm} = -\frac{2d \sin \beta \sin \theta_d}{d^2 - 2d \cos \beta \cos \theta_d + 1}. \quad (14)$$

Obviously (13), (14) are not independent of (7), (8), but related by the unitarity constraint

$$R_t e^{i\beta} + R_b e^{-i\gamma} - 1 = 0. \quad (15)$$

The advantage of expressing  $S_{\pm}$  and  $C_{\pm}$  in terms of  $\beta$  instead of  $\gamma$  is that, at least in the SM, there is now only one manifest weak phase. This implies that, with  $R_t$  determined from  $B$  mixing, both  $d$  and  $\theta_d$  can be extracted from experiment and compared to theoretical calculations, for example QCDF. This is independent of any information from the decay  $B^0 \rightarrow \pi^0 \pi^0$  whose branching ratio continues to be difficult to understand in the framework of QCDF or SCET.

The most accurate measurement of  $\phi_d$  is via mixing in  $B^0$  decays to CP eigenstates of charmonium. The CP asymmetry averaged over these channels provides a direct measurement of  $\sin \phi_d = 0.673 \pm 0.023$ , so that in the SM  $\beta = (21.1 \pm 0.9)^\circ$  [1].<sup>1</sup> It is also possible to derive  $\beta$  from tree-process measurements only, based on  $\gamma$  and  $|V_{ub}|$ . Taking  $\gamma$  and  $|V_{ub}|$  from Ref. [10], see Table 1, we find  $\beta_{\text{tree}}$  using

$$\begin{aligned} \sin \beta_{\text{tree}} &= \frac{R_b \sin \gamma}{\sqrt{1 - 2R_b \cos \gamma + R_b^2}}, \\ \cos \beta_{\text{tree}} &= \frac{1 - R_b \cos \gamma}{\sqrt{1 - 2R_b \cos \gamma + R_b^2}}, \end{aligned} \quad (16)$$

which results in  $\beta_{\text{tree}} = (23.9^{+3.4}_{-3.2})^\circ$  (in the following analysis we use  $\beta_{\text{tree}} = (23.9 \pm 3.3)^\circ$ ). Both values of  $\beta$  are compatible with each other, but we will use the latter one to obtain constraints on a NP contribution to  $\phi_d$ .

From the experimental data collected in Table 2, we find the values of  $d$  and  $\theta_d$  given in Table 3. The high quality of the experimental results leads to small uncertainties on  $d$ , typically 5%, and

<sup>1</sup> There is an ambiguity in this result, as  $\beta = (68.9 \pm 1.0)^\circ$  is also a solution. However, this is excluded at the 95% confidence level by a Dalitz plot analysis of  $B^0 \rightarrow \bar{D}^0 h^0$  where  $h^0 = \pi^0, \omega, \eta$  [12], and by a time-dependent angular analysis of  $B^0 \rightarrow J/\psi K^{*0}$  [13].

**Table 3**

Comparison of  $d$  and  $\theta_d$  derived from experimental results to QCDF predictions for  $\beta_{b \rightarrow ccs}$  from  $b \rightarrow ccs$  transitions and  $\beta_{tree}$  derived from tree decays.

	$\beta_{b \rightarrow ccs} = (21.1 \pm 0.9)^\circ$		$\beta_{tree} = (23.9 \pm 3.3)^\circ$	
	$d$	$\theta_d$	$d$	$\theta_d$
BaBar	$0.790 \pm 0.031$	$0.068 \pm 0.025$	$0.775 \pm 0.037$	$0.075 \pm 0.028$
Belle	$0.803 \pm 0.033$	$0.158 \pm 0.041$	$0.789 \pm 0.040$	$0.174 \pm 0.049$
HFAG	$0.796 \pm 0.021$	$0.104 \pm 0.020$	$0.782 \pm 0.027$	$0.115 \pm 0.025$
QCDF	$0.825^{+0.034}_{-0.052}$	$-0.021^{+0.043}_{-0.042}$	$0.825^{+0.034}_{-0.052}$	$-0.021^{+0.043}_{-0.042}$

moderate uncertainties on  $\theta_d$ . As expected,  $d$  is of order 1, while  $\theta_d$  is rather small.<sup>2</sup>

How do these results compare to theoretical predictions? As mentioned earlier, QCDF provides us with a framework for computing the individual amplitudes contributing to  $B^0 \rightarrow \pi^+\pi^-$ , and the relative phases between them. Complete results for both tree and penguin contributions are available to NLO accuracy [6]. The result for  $A_c/A_u$  is<sup>3</sup>:

$$\frac{A_c}{A_u} = -0.122^{+0.033}_{-0.063} - 0.024^{+0.047}_{-0.048}i. \quad (17)$$

Therefore using  $B_c = A_c - A_u$ ,  $B_t = -A_u$ , we find

$$R_{tc} = \frac{B_t}{B_c} = 0.891^{+0.026}_{-0.050} - 0.019^{+0.037}_{-0.038}i. \quad (18)$$

As  $R_t$  is, by definition, a positive number,  $\theta_d$  is given by the phase of  $R_{tc}$ , as seen in Table 3. The theoretical prediction is ca.  $3\sigma$  away from the experimental (HFAG) result and has the opposite sign. From Eq. (14) it is clear that  $\theta_d$  is mainly constrained by  $C_\pm$ . While Tables 2 and 3 clearly show that the results from BaBar and Belle are not completely in agreement, they *do* agree on the sign and require a positive  $\theta_d$ . This situation is similar to that for  $B \rightarrow K\pi$  decays, where the sign of the observed direct CP violation is difficult to reconcile with QCDF predictions. The source of the discrepancy is independent of any NP contributions to  $\Delta m_{d,s}$ , from which  $R_t$  is determined, as  $\theta_d$  is independent of  $R_t$ . It is also unrelated to any NP contributions to the  $B$  mixing phase  $\phi_d$ , as using the tree-level determination of  $\beta$ ,  $\beta_{tree}$ , for the explicit  $\beta$  dependence renders the discrepancy even slightly worse (right-hand side of Table 3). An explanation in terms of NP could be that an additional NP amplitude contributes to  $B^0 \rightarrow \pi^+\pi^-$ , and we explore this possibility below. Otherwise, the discrepancy may be related to neglected higher order terms in QCDF – either from radiative corrections or terms suppressed by inverse powers of the  $b$  quark mass. As for extreme values of the QCDF input parameters a positive  $\theta_d$  is possible, it would be interesting to see what choice of these parameters yields positive  $\theta_d$  and whether this choice agrees with the scenarios advocated in Refs. [6–8] to reconcile the QCDF predictions for  $B(B^0 \rightarrow \pi^0\pi^0)$  with experimental data.

In order to calculate  $d$  from QCDF we also need  $R_t$ . This can be determined from the ratio of the mass differences in the  $B_s$  and  $B_d$  systems. CDF has made a very clean measurement of  $\Delta m_s$  [16], which can be turned into a value for  $R_t$  using lattice information on the relevant hadronic parameters [11] and Eq. (10). The result is given in Table 1. This value of  $R_t$  allows for a limited

<sup>2</sup> Actually, there is a discrete ambiguity in the determination of  $d$  and  $\theta_d$  which yields a second solution  $d \sim 0.3$  and  $\theta_d \sim 1$ . We discard this solution as  $d$  is the ratio of two tree-dominated amplitudes and hence expected to be close to 1;  $d \sim 0.3$  would imply a massive NP amplitude which cannot be generated in any NP models we are aware of.

<sup>3</sup> Recently the NNLO calculation of the tree amplitude has been completed in Ref. [8]. We do not use this result in our analysis, as we also require the penguin amplitude at NNLO. Nevertheless, we have checked numerically that using this value would alter  $A_c/A_u$  by 4 to 5%.

contribution of NP to the mass differences in the  $B_{d,s}$  systems: from the unitarity relation (15), using  $R_t$  and  $\beta$  as input, one finds  $R_b \approx 0.36$  and  $\gamma \approx 68^\circ$ , in good agreement with the values quoted in Table 1.<sup>4</sup> Combining the QCDF calculation with this value for  $R_t$ , we find that the QCDF prediction agrees with the experimental results within  $1\sigma$ . The experimental results and QCDF predictions for  $d$  and  $\theta_d$  are shown in Fig. 1. The analogous QCDF predictions needed in the “standard” parametrization of  $S_\pm$ , Eq. (7), and  $C_\pm$ , Eq. (8), can be found by dividing (17) by  $R_b$ :

$$r = 0.30^{+0.15}_{-0.09}, \quad \delta + \pi = 0.194^{+0.384}_{-0.382}. \quad (19)$$

Note the difference in the relative errors for  $(d, \theta_d)$  and  $(r, \delta)$ , which is an advantage to the parametrization (9) of the  $B^0 \rightarrow \pi^+\pi^-$  amplitude and will reduce the uncertainties in the constraints on a NP amplitude contribution to this decay.

Let us now discuss constraints on  $\phi_d - 2\beta$ , based on the QCDF results in Table 3. Assuming there is no NP amplitude contributing to the decay, one can obtain  $\beta$  using  $\phi_d$  and the central QCDF values of  $d$ ,  $\theta_d$  as input. This results in  $\beta = 19.9^\circ$  with a minimum  $\chi^2$  of 63. Leaving  $\theta_d$  as fit parameter instead, we find  $\beta = (16.4 \pm 6.5)^\circ$  which shows that the above discrepancy in  $\theta_d$  from QCDF and from experiment is largely irrelevant for NP contributions to  $\phi_d$ . Both values are consistent with  $\phi_d/2 = (21.1 \pm 0.9)^\circ$ , and also with  $\beta = (23.9 \pm 3.3)^\circ$  determined from  $\gamma$  and  $|V_{ub}|$ . However, it is still interesting to note the two results for  $\phi_d/2 - \beta$  are of opposite sign. If there was indeed a NP contribution to  $\phi_d$ , we would expect to see a common trend in the sign of  $\phi_d/2 - \beta$  from various determinations. As this does not seem to be the case, we take this as an indication that any NP contribution to  $\phi_d$  is indeed small.

Given this result, the decay  $B^0 \rightarrow \pi^+\pi^-$  seems then a very suitable place to constrain any NP contributions to the decay amplitude. Such contributions are possible in a variety of NP models, e.g. the 2-Higgs doublet model [17] or R-parity violating SUSY [18]. Therefore, as was done in Ref. [19], we introduce the (complex) NP amplitude  $A_{NP}$  and a new weak phase  $\delta_{NP}$ , such that

$$\lambda_\pm = e^{-i\phi_d} \left( \frac{1 - d e^{i\theta_d} e^{i\beta} + A_{NP} e^{i\delta_{NP}}}{1 - d e^{i\theta_d} e^{-i\beta} + A_{NP} e^{-i\delta_{NP}}} \right). \quad (20)$$

Here  $d$  and  $\theta_d$  are SM quantities, given by the QCDF values stated earlier, in Table 3. The above expression for  $\lambda_\pm$  is actually not suitable to constrain  $A_{NP}$  and  $\delta_{NP}$ : in Ref. [20], it was shown that a given amplitude, with an arbitrary number of distinct weak phases, can always be expressed in terms of any two weak phases. Using this so-called reparametrization invariance,  $\lambda_\pm$  can be expressed in terms of the two weak phases  $\phi_d$  and  $\beta^5$ :

$$\lambda_\pm = e^{-i\phi_d} \left( \frac{1 - d' e^{i\theta'_d} e^{i\beta}}{1 - d' e^{i\theta'_d} e^{-i\beta}} \right), \quad (21)$$

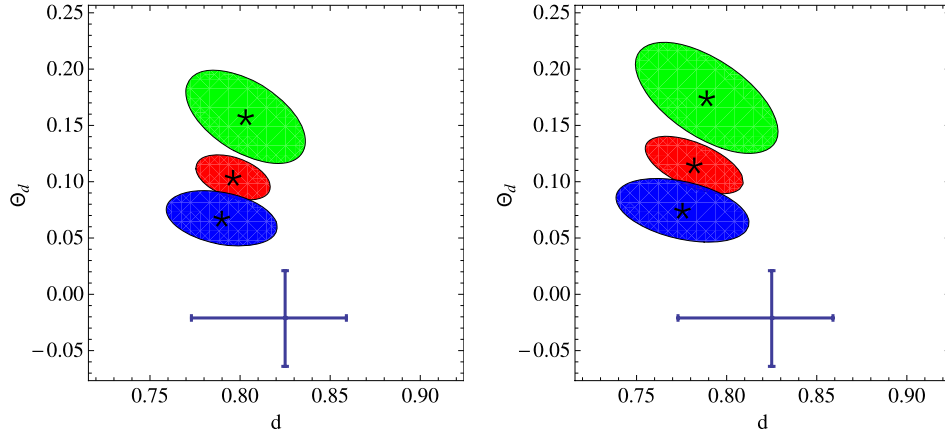
where

$$d' e^{i\theta'_d} = \frac{d e^{i\theta_d} - A_{NP} \sin(\delta_{NP}) / \sin \beta}{1 + A_{NP} \sin(\beta - \delta_{NP}) / \sin \beta}. \quad (22)$$

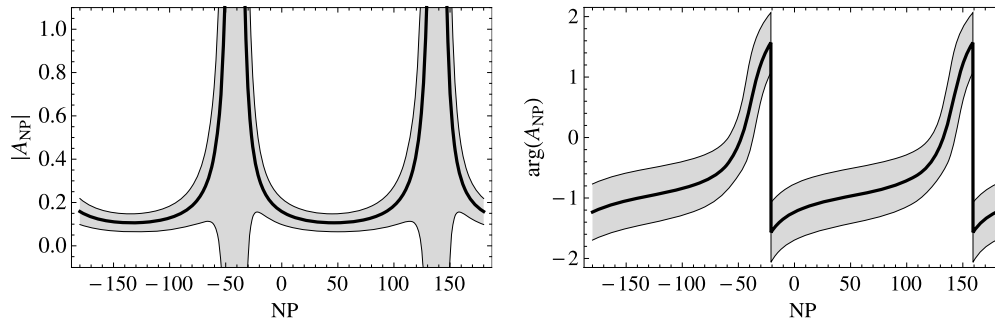
Note that  $d' e^{i\theta'_d} \rightarrow d' e^{i\theta'_d}$  under a CP transformation, so  $\theta'_d$  is indeed a strong phase. In Eq. (21),  $\phi_d$  is, by definition, the phase measured in  $B$  mixing, i.e. from  $b \rightarrow ccs$  transitions, while  $\beta$  is obtained from tree-level processes, i.e.  $\phi_d = (42.2 \pm 1.8)^\circ$  and  $\beta = (23.9 \pm 3.3)^\circ$ . The values for  $d'$  and  $\theta'_d$  are obviously identical to the experimental results for  $d$  and  $\theta_d$  in Table 3. The resulting constraints on  $A_{NP}$

<sup>4</sup> The agreement is not perfect for  $R_b$ . If, however, one uses the result for  $|V_{ub}| \approx 3.5 \times 10^{-3}$  from exclusive decays, instead of the larger PDG value,  $R_b \approx 0.36$  and the agreement is near perfect.

<sup>5</sup> Eq. (21) was already obtained in Ref. [20], as (48).



**Fig. 1.** The allowed experimental region for  $d$  and  $\theta_d$  are plotted for the case  $\beta = (21.1 \pm 0.9)^\circ$  on the left and  $\beta = (23.9 \pm 3.3)^\circ$  on the right. The blue (lower) region corresponds to the results for  $S_\pm$  and  $C_\pm$  of BaBar, the green (upper) region corresponds to those of Belle and the red (central) region corresponds to the average given by HFAG as in Table 2. The blue point with error bars represents the QCDF prediction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)



**Fig. 2.**  $|A_{NP}|$  and  $\arg(A_{NP})$  plotted against the weak phase of the new physics amplitude,  $\delta_{NP}$ . The thick black lines represent the results found using the experimental average value of  $\sin(\phi_d)$ , and central values of all other input parameters. The grey regions include effects due to all experimental and parametric uncertainties.

and  $\delta_{NP}$  are shown in Fig. 2. Depending on the value of  $\delta_{NP}$ , large NP contributions  $|A_{NP}|$  are possible. Note that these results are mainly due to the discrepancy between  $\theta'_d$  from experiment and  $\theta_d$  from QCDF. In particular, even for  $\delta_{NP} = 0$  a non-zero  $|A_{NP}| \approx 0.1$  is needed. Also note that the allowed value for  $|A_{NP}|$  can be as large, or even larger, than the SM (QCDF) prediction for  $d$ . Although it would be interesting to interpret the NP amplitude in terms of the NP models mentioned, making use of constraints from other processes, this is beyond the scope of this Letter.

In summary, we have investigated the effect of NP on the decay  $B^0 \rightarrow \pi^+\pi^-$ . We first analysed the CP asymmetries in the SM, using a particularly convenient parametrization of the decay amplitude which depends on only one weak phase,  $\beta$ . We compared the experimental results of the relevant hadronic quantities with those from theoretical calculations, using QCDF. We found that while the size of the strong amplitude is consistent, its predicted phase  $\theta_d$  deviates from experiment by  $\sim 3\sigma$ . It would be interesting to study whether the choice of QCDF input parameters minimising this discrepancy is the same needed to reduce that between the predicted and observed branching ratio of  $B^0 \rightarrow \pi^0\pi^0$ . We then analysed the implications for NP contributions to the decay. Under the assumption that NP modifies only the phase in  $B$  mixing, the discrepancy in the strong phase was largely irrelevant and the NP contributions to the mixing phase found to be consistent with 0. We then allowed for a NP amplitude contributing to the decay amplitude of  $B^0 \rightarrow \pi^+\pi^-$  and analysed the CP asymmetries exploiting the constraints imposed by reparametrization invariance. Here we found scope for large

NP contributions, which are driven by the discrepancy between  $\theta_d$  from experiment and from QCDF. An analysis of this NP amplitude within specific models is beyond the scope of this Letter.

## References

- [1] E. Barberio, et al., Heavy Flavor Averaging Group, arXiv:0808.1297 [hep-ex], and online updates at [www.slac.stanford.edu/xorg/hfag](http://www.slac.stanford.edu/xorg/hfag).
- [2] A.J. Buras, R. Fleischer, S. Recksiegel, F. Schwab, Eur. Phys. J. C 45 (2006) 701, arXiv:hep-ph/0512032; M. Bona, et al., UTfit Collaboration, JHEP 0603 (2006) 080, arXiv:hep-ph/0509219; P. Ball, R. Fleischer, Eur. Phys. J. C 48 (2006) 413, arXiv:hep-ph/0604249.
- [3] M. Gronau, D. London, Phys. Rev. Lett. 65 (1990) 3381.
- [4] R. Fleischer, Phys. Lett. B 459 (1999) 306, arXiv:hep-ph/9903456; A. Soni, D.A. Suprun, Phys. Lett. B 635 (2006) 330, arXiv:hep-ph/0511012.
- [5] M. Beneke, G. Buchalla, M. Neubert, C.T. Sachrajda, Phys. Rev. Lett. 83 (1999) 1914, arXiv:hep-ph/9905312.
- [6] M. Beneke, S. Jäger, Nucl. Phys. B 751 (2006) 160, arXiv:hep-ph/0512351; M. Beneke, S. Jäger, Nucl. Phys. B 768 (2007) 51, arXiv:hep-ph/0610322.
- [7] V. Pilipp, Nucl. Phys. B 794 (2008) 154, arXiv:0709.3214 [hep-ph]; G. Bell, Nucl. Phys. B 795 (2008) 1, arXiv:0705.3127 [hep-ph].
- [8] G. Bell, Nucl. Phys. B 822 (2009) 172, arXiv:0902.1915 [hep-ph].
- [9] C.W. Bauer, I.Z. Rothstein, I.W. Stewart, Phys. Rev. D 74 (2006) 034010, arXiv:hep-ph/0510241.
- [10] C. Amsler, et al., Particle Data Group, Phys. Lett. B 667 (2008) 1.
- [11] E. Gamiz, et al., HPQCD Collaboration, arXiv:0902.1815 [hep-lat].
- [12] B. Aubert, et al., BaBar Collaboration, Phys. Rev. Lett. 99 (2007) 231802, arXiv:0708.1544 [hep-ex]; K. Abe, et al., arXiv:hep-ex/0507065.
- [13] B. Aubert, et al., BaBar Collaboration, Phys. Rev. D 71 (2005) 032005, arXiv:hep-ex/0411016;

- R. Itoh, et al., Belle Collaboration, Phys. Rev. Lett. 95 (2005) 091601, arXiv:hep-ex/0504030.
- [14] B. Aubert, et al., BaBar Collaboration, arXiv:0807.4226 [hep-ex].
- [15] H. Ishino, et al., Belle Collaboration, Phys. Rev. Lett. 98 (2007) 211801, arXiv:hep-ex/0608035.
- [16] A. Abulencia, et al., CDF, Phys. Rev. Lett. 97 (2006) 062003, arXiv:hep-ex/0606027.
- [17] Z. Xiao, C.S. Li, K.T. Chao, Phys. Rev. D 63 (2001) 074005, arXiv:hep-ph/0010326.
- [18] G. Bhattacharyya, A. Datta, A. Kundu, J. Phys. G 30 (2004) 1947, arXiv:hep-ph/0212059.
- [19] A. Jain, I.Z. Rothstein, I.W. Stewart, arXiv:0706.3399 [hep-ph].
- [20] F.J. Botella, J.P. Silva, Phys. Rev. D 71 (2005) 094008, arXiv:hep-ph/0503136.